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Photogrammetric Engineering & Remote Sensing

Tactical Mobility Modeling for REFORGER 87

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ABSTRACT: The Waterways Experiment Station (WES) responded to requests by the U.S. Army III Corps, 64th Engineer Detachment (Terrain) by providing trafficability support for the REFORGER 87 military exercises in the Federal Republic of Germany. The maneuver area covered 25 1:50,000-scale topographic map sheets. A digital mobility database was developed within a period of one month. A principal source of information was Landsat Thematic Mapper (TM) data, which was integrated with various other digital factor maps necessary for computer modeling of vehicle mobility. The Condensed Army Mobility Model System (CAMMS) was used to evaluate the performance of specified vehicles operating off-road in the maneuver area. CAMMS correctly predicted a NOGO situation for an area where several U.S. armored vehicles were immobilized when a gravel road failed and the vehicles were unable to traverse the surrounding organic clay soil and associated drainage ditches.

INTRODUCTION

BACKGROUND

In January 1987, the U.S. Army III Corps, 64th Engineer Detachment, began planning for the 1987 REFORGER (Return of Forces to Germany) military exercises to be held in September of that year. On 30 June 1987, a formal request for WES's support for mobility analyses was made by III Corps. The area of operations consisted of 25 1:50,000-scale topographic maps located in the State of Lower Saxony. It was requested that WES develop a digital mobility database covering the exercise area and provide the necessary hardware, software, and technical support for trafficability analyses in the field. Due to the size of the study area and time constraints, it was decided that land-cover delineation by manual cartographic and digitization techniques was impractical. However, derivation of land-cover information from digital satellite data was feasible. Landsat Thematic Mapper data are the preferred data source for most mobility and combat modeling applications at WES (Lashlee and Overton, 1991). Only upon confirmation of the existence of appropriate TM data was the decision made to develop the digital data base (Figure 1). A project methodology and time schedule were developed and data processing began on 5 August 1987.

THE RETURN OF FORCES TO GERMANY

The United States has joined NATO for the annual REFORGER military exercises since 1969. REFORGER 87 was designed to emphasize the U.S. capability to transport an entire Corps of combat forces for rapid reinforcement of Europe. Most of these deploying units utilize equipment and material prepositioned in Europe as part of NATO strategy. The purpose of these exercises is to deter war in Europe. The exercise showed visiting communist officials that NATO Doctrine is defensive in nature (Cox, 1988).

Exercise CERTAIN STRIKE, the ten-day battle phase of REFORGER 87, began on 14 September 1987 and simulated a Soviet and Communist East Block offensive thrust across the inner-German border, into the northern plains of the Federal Republic of Germany. A total of 115,000 NATO military personnel from six NATO nations, including 35,000 U.S. combat soldiers, participated in the exercise. Other participating NATO countries and approximate military personnel were the Federal Republic of Germany (19,000), The Netherlands (11,100), United Kingdom (7,000), Belgium (6,000), and France (200). Twenty-thousand wheeled vehicles, 2,200 light armored vehicles, 700 main battle tanks, and 250 Howitzers and Multiple Launched rocket systems were deployed to the 400 square kilometre maneuver box. REFORGER 87 was the largest deployment of U.S. forces since World War II (Cox, 1988).

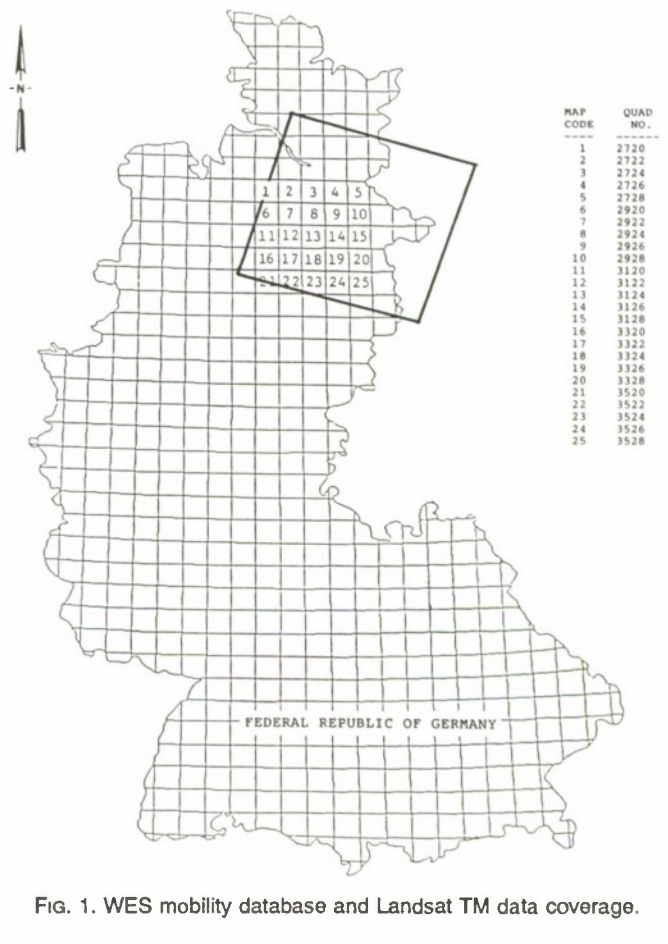

FIG. 1. WES mobility database and Landsat TM data coverage.

STUDY AREA

The North German Plain, one of four physiographic provinces, covers approximately one-third of the Federal Republic of Germany and is characterized by landforms that have developed almost exclusively in glacial deposits. It is primarily a

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region of moraines and glacio-fluvial sediments (Hagedorn, 1989). Soils in this area are generally coarse grained sands and silts with isolated occurrences of fine grained and organic soils. Drainage in the area consists of the Aller, Wesser, and Elbe Rivers, and their tributaries, which drain into the North Sea. The topography is generally flat to rolling with local differences in elevation between 76 and 152 metres (250 and 500 feet) above mean sea level. Slopes are usually less than 10 percent, but can be as steep as 45 percent on isolated landforms. The North German Plain generally affords good cross country movement during the dry months. However, numerous marshlands, peat bogs, canals, small streams, and an extensive network of drainage ditches are common obstacles to off-road mobility. The tactical exercise box covered 400 square kilometres, ranging from the city of Hannover, Lower Saxony's Capital city, to the Elbe River in the Northeast. Lower Saxony has a population of 7.3 million.

MOBILITY MODELING

AMM, NRMM, AND CAMMS

Mobility models are comprehensive analysis tools designed to objectively evaluate the on- and off-road mobility of vehicles by means of digital computer simulation. Military ground vehicle field testing and mathematical modeling have been conducted at WES since World War II. Results of these tests and models were consolidated in a computerized mobility model in 1971. The Army Mobility Model (AMM) predicts vehicle trafficability as a function of the vehicle, driver, terrain, weather, and scenario factors that influence on-road, off-road, and gap crossing vehicle mobility. The AMM software has undergone extensive field testing and validation. In 1978, the AMM was accepted as Edition 1 of the NATO Reference Mobility Model (NRMM). Internationally accepted, the NRMM includes vehicle mobility prediction relations that are modified only by formal consensus of the NATO countries that use the NRMM (Turnage, 1989). The AMM and NRMM have been used extensively in U.S. military vehicle acquisition programs.

The Condensed Army Mobility Model System (CAMMS) was developed by WES in 1983. A derivative of the AMM, CAMMS is a vehicle mobility analysis model designed for U.S. Army tactical applications. CAMMS provides a comprehensive description of the ability of vehicles and vehicle convoys to transport men and material over virtually any type of terrain and under nearly any weather condition (Butler, 1988). Other CAMMS capabilities include the following:

- Cross country mobility predictions
- On-road mobility predictions
- Foot soldier mobility predictions
- Maneuver damage assessments
- Unassisted gap-crossing potential
- Fixed bridge crossing potential
- Interactive route evaluation
- Tactical bridge emplacement
- Obstacle effectiveness
- Route network evaluation
- 3D perspective view
- Line of sight
- Weapon effectiveness
- Potential landing zones

A powerful feature of CAMMS, as compared to the AMM, is the capability to change soil strength based on current weather conditions. The Soil Moisture Soil Strength Prediction (SMSP) Model predicts soil strength for all combinations of 16 Unified Soil Classification System soil types; six wetness indices (arid, dry, average, wet, saturated, waterlogged); and three scenario types (seasonal, current, projected).

The SMSP makes predictions based on historical precipitation data, precipitation measured for the prior 24-hour period, and from the current soil moisture content adjusted by the forecasted precipitation for multiples of 24 hours (Butler, 1988).

DIGITAL MOBILITY DATA BASE DEVELOPMENT

DIGITAL IMAGE ANALYSIS

TM bands 2,3,4, and 5 were chosen for image processing. The software used to process these data was the Earth Resources Laboratory Applications Software (ELAS), developed by the National Aeronautics and Space Administration (NASA) (Graham *et al.*, 1980). Thirty-six unsupervised training statistics were calculated with a window based clustering algorithm. The definition of a homogeneous training field is a 3 by 3 window with a standard deviation between user selected homogeneity parameters for the standard deviation lower bound (Default = 0.1) and either the standard deviation upper bound (Default = 1.0) or the coefficient of variation (Default = 5 percent) times the mean of the window values. Each statistic accepted by the program consists of the mean, standard deviation, and covariance of a homogeneous 3 by 3 window of pixels.

After the initial statistics were calculated, a procedure was executed to merge similar candidate statistics into a manageable, user defined number of final statistics, thus insuring a minimum statistical scaled distance between the means of the statistics. The scaled distance equation is essentially the square root of the sum of squares of the differences in the means between a pair of statistics, normalized by the variation in each band at the merged mean.

To maximize the overall classification accuracy, a Bayesian classification algorithm was used to assign each pixel to a land cover category. The ELAS Bayesian classifier uses the *a priori* probabilities determined from the number of pixels collected in each statistic in an equation to determine the probability that a given pixel vector **X** belongs to a class.

Ground photographs, orthophotographic maps, German produced military topographic maps, engineering geology maps, statistical field data, and previous field experience of WES personnel were used to assign information classes to the 36 spectral classes. The land-cover image was georeferenced to a Universal Transverse Mercator map projection and resampled to 100-metre spatial resolution for compatibility with other factor maps developed for mobility modeling. A post-classification program was used to condense the land-cover information into 11 final classes needed to quantify the study area for mobility analyses.

CLASSIFICATION OF URBAN AREAS FOR MOBILITY MODELING APPLICATIONS

A problem with classification of urban areas for mobility modeling applications was identified at this stage of the data-base development. Mobility and combat modeling applications are characterized by relatively large areas of strategic interest. Topographic maps are often outdated and sometimes not available. It is desirable to develop automated urban extraction techniques for topographic map revision of urban growth. Most urban mapping techniques are based on deriving quantitative information on the amount and/or location of the individual land covers within urban areas. For mobility modeling analyses, only an accurate urban boundary delineation is required. The AMM and CAMMS use empirical mathematical algorithms and a digital database to predict the performance of a vehicle in terms of speed. These models assign all vehicles a constant speed in urban areas, based on the assumption that a vehicle will travel on a hard-surface road whenever possible. Urban areas are divided into three classes based on size: villages, towns, or cities.

The time it takes a vehicle to traverse an urban area is a function of the size of the urban area.

Traditional image classification techniques failed to delineate urban boundaries accurately. Urban areas were extracted from 1:50,000-scale topographic maps. Automated urban boundary delineation for mobility modeling was identified as a research interest, the results of which are documented in Naugle *et al.* (1991).

Geographic Information Systems

Mobility and combat modeling digital databases require accurate physiographic information, specifically: vegetation, slope, elevation, soils, hydrology, urban, and road location and descriptions. In addition to these maps, some models require obstacles, vegetation height, surface roughness, trafficability, visibility, landform classification, tree stem spacing, and bridges (Mason *et al.*, 1990). These data are derived either directly from available source material or translated indirectly from statistical ground verification data.

The U.S. Army III Corps, 64th Engineer Detachment, provided topographic and other special product maps required for WES to produce basic factor maps needed to develop a digital mobility database. Required data were extracted from available sources, then digitized, encoded, and processed using the Geographic Information System software. Digital Terrain Elevation Data (DTED) Level I were acquired from the Defense Mapping Agency. The algorithm used to calculate slope from the DTED data is a vector based slope program described in Ritte (1987). Terrain factors from all sources were land cover, slope, soil type, vehicle obstacles, and urban areas.

HARDWARE SUPPORT

These data were transformed into a mobility database using translation routines developed at WES from field verification and statistical data collected in the Federal Republic of Germany. The database was stored on a Zenith 248 microcomputer system which included an Optotech 200 megabyte (Mb) optical disk drive for data storage, EGA color graphics card and color monitor, an 80287 math coprocessor, 2.5 Mb of expansion memory, two 20 Mb hard disk drives, and 360 Kilobyte and 1.2 Mb floppy disk drives. A Graphtec MP2300XY color pen plotter was used for hardcopy map production.

SOFTWARE SUPPORT

Color mobility and terrain description maps were displayed on the microcomputer monitor. A device driver for the pen plotter was developed to produce color hardcopy products plotted at scales of 1:50,000, 1:100,000, and 1:250,000. Due to the severe time constraints, the software driver for the pen plotter was not finished prior to departure from WES. It was completed and refined to meet system specifications during the first week of field support, prior to the maneuver period of REFORGER 87. WES met the requested support requirements, and personnel were present at the III Corps Headquarters in the Federal Republic of Germany at the start of the REFORGER exercises, 1 September 1987.

FIELD SUPPORT

The WES field support team consisted of a physical scientist, a research civil engineer, an electronics engineer, and a computer programmer. Preliminary database verification was performed during the initial days of the exercise. The WES-produced land-cover definition was compared to special map products and a variety of TM false color and pseudocolor composites at 1:100,000 scale. Ground verification data were collected repeatedly during the exercise. The land-cover factor map was found to be an accurate level II land-cover classification.

Rain gauges and soil trafficability kits were used to collect site specific precipitation, soil moisture, and soil strength measurements on a daily basis. Cone index (CI) measurements were acquired with the standard WES cone penetrometer for depths ranging from 0 to 91 cm (0 to 36 inches). The CI value represents the resistance of the soil to penetration of a 30 degree cone of 3.22 cm^2 (0.5 square inch) base and is an index of the shearing resistance of the soil. Although considered dimensionless, the CI actually denotes the pounds of force on the instrument handle divided by the area of the cone base in square inches. The CI is a measure of *in situ* soil strength.

Remolding indices (RI) were taken to measure that portion of the original soil strength that would be retained under traffic. The RI is a ratio of the CI of a remolded soil sample to the CI of that soil sample before remolding. A soil is remolded with a WES standard soil compaction test, in which a sample is placed in a 5.08 cm (2 inch) diameter tube and deformed with a 4.54 kilogram (10 pound) hammer one hundred times. It expresses the change in strength of a fine grained soil or a sand with fines, poorly drained, that may occur under traffic of a vehicle.

From these data, Rating Cone Indices (RCI) were calculated. The RCI is the product of the measured cone index and remolding index for the critical soil layers, 0 to 15 and 15 to 30 centimetres (0 to 6 and 6 to 12 inches). This index is valid for only fine-grained soils and for sands with fines, poorly drained. Trafficability is the capacity of a soil to support the traffic of a vehicle and is generally defined in terms of the number of passes a vehicle can complete in trace before immobilization on a given soil type and strength. The vehicle cone index (VCI) is that soil strength in terms of RCI for fine grained soils and CI for coarse grained soils, required for a vehicle to make a given number of passes in a trace. Soil samples were also collected and oven dried at the III Corps Headquarters for determination of soil moisture content. Field data were incorporated in CAMMS to enhance mobility and speed predictions on a daily basis for selected vehicles.

A problem area identified during field reconnaissance was the evaluation of vehicle mobility in peat soils. The peat bogs in this area afford relatively poor cross country mobility because they are either poorly drained or are drained by extensive drainage ditches. Field data were collected at peat bog sites and adjustments were made to the CAMMS to correctly model these features. The incorporation of field verification data and the ability to quickly modify software for specific landforms demonstrated the flexibility and utility of CAMMS. WES products were used by the 64th Engineer Detachment for briefing and distribution to III Corps Divisions. Specific map products of interest were the number of passes in trace (based on soils only); number of passes in trace (based on all terrain features); and vehicle speed (based on all terrain factors).

VEHICLE IMMOBILIZATION

The WES information correctly predicted a NOGO situation in an area where several U.S. armored vehicles were immobilized when a gravel road being traveled failed and the vehicles were unable to traverse the surrounding high plasticity organic clay soil and associated drainage ditches (Plate 1). Because the water table was found to be within 30 cm (12 inches) of the surface, it was not possible to extract soil samples to perform a soil remold test necessary for determining the rating cone index of the soil. With an *a priori* knowledge of the expected remold index to range from 0.2 to 0.5 at the critical soil layer for these vehicles, the probable RCI for the 30 to 45 cm (12 to 18 inch) layer would have been less than the vehicle cone index for one pass (VCI_1) of an M1A1 main battle tank. A VCI_1 larger than the RCI resulted in an immobilization due to soft soil as predicted with the CAMMS model.

**REFORGER 87 FEDERAL REPUBLIC OF GERMANY
EXERCISE CERTAIN STRIKE**

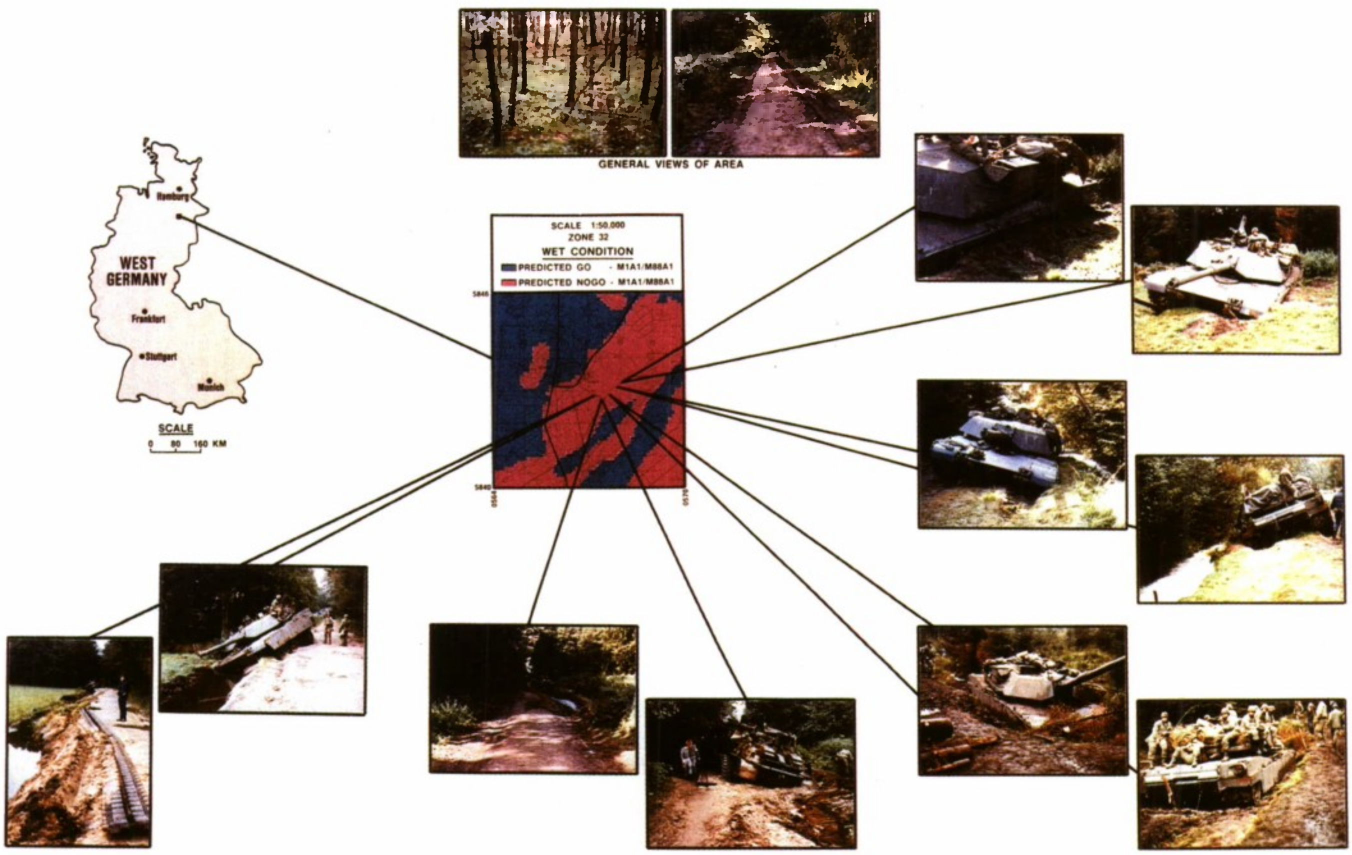

PLATE 1. The CAMMS mobility prediction and vehicle immobilization.

The 64th Engineer Detachment had briefed military planners at headquarters on off-road trafficability conditions for this area with CAMMS products. However, it was not anticipated that a one-kilometre section of road would fail in several locations, stranding a column of vehicles and forcing some vehicles to attempt cross country movement. The cost of this immobilization in terms of maneuver damage and reclamation, including rebuilding the road, was extensive. A total of 16 million dollars was allocated for vehicle maneuver damage for the REFORGER 87 military exercises. A portion of this money was used for reclamation of the immobilization site.

CONCLUSIONS

The success of the WES support to the U.S. Army III Corps, 64th Engineer Detachment during the 1987 REFORGER military exercises was measured by the following criteria: digital analysis of Landsat TM data allowed WES to provide the requested support in a time and cost effective manner necessary for military applications; the CAMMS microcomputer capability as a tactical decision aid was successfully demonstrated to and preferred by the 64th Engineer Detachment compared to manually mapped cross country mobility products and a German produced, engineering based, hardcopy product; and WES products were used to brief U.S. Army exercise planners on changing trafficability conditions. REFORGER 87 also provided a good testbed for a WES developed maneuver damage algorithm used to forecast maneuver damage based on V Corps assessment criteria and the relationships between vehicle trafficability and soil strengths.

CAMMS has been applied successfully in a number of U.S. Army exercises including REFORGER 86, BOLD ADVENTURE 87, TEAM SPIRIT (87), CASCADE PEAK IV (87), REFORGER 87, REFORGER 89, and REFORGER 90 (Turnage, 1989). CAMMS has also been designated the mobility prediction model within several major ongoing Army programs: the AirLand Battlefield Environment technology demonstration program of the U.S. Army Corps of Engineers, the Digital Topographic Support System, the Battle Command Training Program, and the FORSCOMM Automated Intelligence Support System. CAMMS was recently fielded in Operations DESERT SHIELD and DESERT STORM.

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Forum

Topographic Normalization in Rugged Terrain

While Colby (1991) raises some interesting questions about appropriate normalization techniques for rugged terrain, the test statistics used to compare models are unclear. Equation 1 specifies a Minnaert constant model as

$$L(\lambda,e) = \mathrm{Ln}(\lambda)\cos^{(k\lambda)}i\cos^{k(\lambda)-1}e,$$

where $k(\lambda)$ and $\mathrm{Ln}(\lambda)$ are parameters to be estimated by the linear regression applied to a log form of the above equation. Should the model be correctly specified, an assumption required for test statistics to be valid, including the usual additive error term, ϵ, and subscripts to denote target, t, and pixel, j, Equation 1 becomes

$$L_{tj}(\lambda,e) = \mathrm{Ln}_t(\lambda)\cos^{k(\lambda)}i_{tj}\cos^{k(\lambda)-1}e_{tj}, + \epsilon_{tj}.$$

Linear regression using the log form is only appropriate should the error term be multiplicative, though non-linear least squares would provide similar parameter estimates and hypothesis testing.

Though the author references a one-way analysis of variance to test the hypothesis that the mean corrected radiance values for each site are equal:

$$H_0\text{: } \mathrm{LN}_1 = \mathrm{Ln}_2$$
$$H_A\text{: } \mathrm{Ln}_1 \neq \mathrm{Ln}_2,$$

no reference is made as to whether the F-test statistics provided in Tables 2 and 3 test the above hypothesis, or correspond to the homogeneity of variance test given by the author as

$$F = \frac{\text{mean squared error between (original)}}{\text{mean squared error between (normalized)}}.$$

While unequal error variances (between sites) would tend to result in an overstatement of the significance of the equality of means F-tests, the appropriate F-test for equality of variance would be to ratio the mean squared errors for each site (Snedecor and Cochran, 1967). For the F-statistic to be appropriate, the numerator and denominator sum of squares must be independent and χ^2 distributed under the null hypothesis (Morrison, 1976). Should the normalization procedure given by Equation 4 be used to calculate the demonimator sum of squares, these conditions would not be met. In general, because a transformation of a random variable **Y**, to $\mathbf{Z} = a\mathbf{Y}$ results in the Var(**Z**) $= a^2$ Var(**Y**), the F-ratio, as it appears to be stated above, would yield an expected value of Var(**Y**)/Var(**Z**) $= 1/a^2$, rather than the expected value of 1. The usual test for equality of means is the F-ratio of the mean sum of squares due to regression to the mean sum of squares due to error (Draper and Smith, 1966). A test to compare the Minnaert model to the original data is possible by adding a constant term, c_t, to Equation 1 and possibly overfitting the model:

$$L_{tj}(\lambda,e) = c_t + \mathrm{Ln}_t(\lambda)\cos^{k(\lambda)}i_{tj}\cos^{k(\lambda)-1}e_{tj} + \epsilon_{tj}.$$

Should the confidence interval for Ln_t contain zero, then evidence supporting the Minnaert model over a simple site average, c_t, does not exist. Should the hypothesis that $k(\lambda_1) = k(\lambda_2)$ be rejected, then the data would suggest that band ratioing for bands λ_1 and λ_2 is inappropriate.

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Response

In her comment on the article, "Topographic Normalization in Rugged Terrain," the author raises two points concerning the clarity of the test statistics, and three suggestions regarding applications. The points refer to

- the nature of the distribution of the error terms resulting from a linear regression using the log form of Equation 1, and
- clarification of the correspondence between statistical tests and the tables of results.

The suggestions refer to

- the use of $1/a^2$ in the homogeneity of variance test rather than assuming a 1/1 relationship,
- the use of an "overfitted" model, and
- the appropriateness of the band ratio technique if the Minnaert constants for the bands are not equal.

The first point states that linear regression using the log form of Equation 1 is only appropriate should the error term be multiplicative. Equation 1 and the succeeding linear and log transformations were obtained from Smith *et al.* (1980), and are so referenced. The procedure was used to derive the Minnaert constant (k) by Smith *et al.* (1980), Justice and Holben (1979), and Justice *et al.* (1980). The first two articles are referenced in the Second Edition of the *Manual of Remote Sensing*, in the chapter "Removal of Topographic Effects" (Estes *et al.*, 1983). I am aware of no evidence to believe that the assumption made in previous research regarding the multiplicative nature of the error term in Equation 3 is incorrect. In fact, in Smith *et al.* (1980), Figure 3 displays the scatter of data resulting from the linear log transformation of Equation 2 (Smith *et al.*, 1980), Equation 1 (Colby, 1991). Inspection of the distribution of residuals in the scatterplot for bands 5 and 7 suggests that the errors would be multiplicative rather than additive.

The second point describes the null and research hypotheses of the one-way analysis of variance as pertaining to the mean corrected radiance values for each site, whereas the F-test statistics for the one-way analyses of variance were derived from the relationship between the three separate sample sites of the digital images of bands 2, 3, 4, and 5. The research and null hypotheses for the one-way analyses are stated in the text of the paper, and the resulting F-statistics are listed in Table 2. The reduction of the F-statistics from the same band images before and after normalization is being highlighted, together with a comparison of the F-statistics derived from the band ratio technique, and between forested sample sites, and forested-rocky ground (different cover type) sample sites. The null and research hypotheses for the homogeneity of variance test are not explicitly stated in the original paper, but are similar as for the one-way analyses of variance; that is,

$$H_o: \sigma_1^2 = \sigma_1^2$$
$$H_A: \sigma_1^2 \neq \sigma_2^2$$

The F statistics testing for the homogeneity of variances between images for bands 2, 3, 4, and 5 are listed in Table 3.

Addressing the first suggestion, an analysis using $1/a^2$ in place of 1/1 was undertaken using the mean values of cos i and cos e (excluding extremes) for the pixels of sample sites 1, 2, and 3 for band images 2, 3, 4, and 5. The results show $a^2 = 1.12$ (band 2), 1.28 (band 3), 1.46 (band 4), and 2.6 (band 5). With F statistic and a^2 values calculated using Minnaert constants derived from the entire image, the results of the homogeneity of variance tests found that the difference between the original and normalized images were significant at 0.13 (band 2), 0.06 (band 3), 0.12 (band 4), and 0.18 (band 5). However, if the more accurate Minnaert constants derived from the site values were used to both normalize the original image and to calculate a^2, then the above significance thresholds are expected to decrease, as suggested in Colby (1991). For example, if the Minnaert constant derived from the sample sites for band 3 is used just in the calculation of a^2, then the threshold drops to 0.03, which would be statistically significant. It should be kept in mind that the test for the homogeneity of variances measures a reduction in variability which is generally being interpreted as a measure of the reduction of the topographic effect. As with the previous comparison of F statistics from the one-way analyses of variance, statistical significance is not a requirement to consider the technique effective.

The suggestion of using the "overfitted" model is already incorportated in determining the slope of the regression line (the Minnaert constant). According to previous research, if the confidence interval for Ln contains 0, then the non-Lambertian assumption is not valid and the Lambertian model may be more appropriate (Smith *et al.*, 1980).

Regarding the final suggestion, the slope of the regression line which determines the Minnaert constant is spectrally dependent; therefore, it is doubtful that the constants for different bands will be the same for one image. Information from the relationship between the spectral reflectance responses in different wavelengths for the same phenomena is sought through band ratios. Requiring equal Minnaert constants as a pre-condition for the use of a band ratio would severely limit the information that could be extracted, and in any case would be a pre-condition that rarely could be met. The band ratio technique may be useful in some applications, for example, visual inspection of an image with some removal of the topographic effect.

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